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Investigating the effect of adding silver nanoparticles to hybrid crystalline silicon solar cells

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ABSTRACT

Hybrid silicon solar cells are an implementation of solar cells which have a simple fabrication process meanwhile absorbing a wider range of light spectrums compared to common silicon solar cells, although hybrid silicon solar cells have relatively low efficiencies. Metal nanoparticles have been known to enhance the performance of solar cells due to their localized surface plasmon resonance effect. The present study evaluates the addition of silver nanoparticles to enhance the properties and performance of hybrid silicon solar cells. In this regard silver nanoparticles are added to hybrid silicon solar cells producing different layer combinations in hybrid silicon solar cells. According to the results the addition of silver nanoparticles in specific combinations may enhance the performance whereas in other combinations may destroy the photovoltaic characteristics of the hybrid solar cell. A certain combination of the hybrid silicon solar cells including silver nanoparticles has been proposed wherein the properties of the cell are enhanced due to the plasmonic effect of silver nanoparticles. However, silver nanoparticles added on the surface of the photovoltaic cells cause shading, thus decreasing the active surface of the cell and thereby reducing the efficiency of the cells. Therefore, there is an optimum surface distribution for silver nanoparticles to benefit from the localized surface plasmon resonance effect meanwhile not shading a large amount of the cell and reducing the active surface area of the cell which is evaluated in the present research. Accordingly, by adding silver nanoparticles from a solution of 50% vl concentration the efficiency of the hybrid silicon cell reached 3.7% which is a significant increase compared to the efficiency of the ordinary hybrid silicon solar cells which was 1.8%.

1. Introduction

Several researches have been conducted to enhance the performance and increase the efficiency of crystalline silicon solar cells. One of the methods of enhancing the performance of solar cells is with the aid of nanotechnology, which includes adding nanoparticles to the structure of solar cells. Different types of nanoparticles have been used for this purpose. In this regard metal nanoparticles have been of great interest due to the local surface plasmon resonance (LSPR) effect. LSPR is an excitation occurring on the metal surface which may be caused by near-infrared, visible light and Ultraviolet waves.

The LSPR effect depends on the material, shape, and size of the nanoparticle. As an example, Dlamini et al. (2020) have used zinc sulphide nanoparticles to enhance the photocurrent in organic solar cells. Although, gold and silver nanoparticles have been commonly used to enhance the performance of solar cells due to their reasonable light-trapping properties (Ho et al., Jun. 2017). In this regard, Kaçuş et al. (2021) studied the effect of adding both silver and gold nanoparticles on the optical and electrical properties of organic silicon solar cells. Zarei and Emami (2020) used Au-ITO core–shell nanoparticles to increase absorption of organic solar cells. Among the most commonly used nanoparticles to enhance the efficiency of solar cells are silver nanoparticles. Some examples of the application of silver nanoparticles in different types of solar cells are described below. In this regard, some researchers have worked on the application of silver nanoparticles in organic solar cells, such as, Salim et al. (2020) who studied the application of silver nanoparticles with a core–shell structure to optimize the performance of organic solar cells. Toe et al. (2020) used a combination of silver nanoparticles and ZnO nanorods to enhance the localized surface plasmon resonance properties.

Additionally, researchers have also studied the application of silver nanoparticles on other types of solar cells. As an example, Tay et al. (2020) used silver nanoparticles to increase the power absorption efficiency of amorphous silicon solar cells. Ho et al. (2020) used silver nanoparticles to enhance the localized surface plasmon resonance in

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Nomenclature

V_{oc}	Open circuit voltage
DLS	Dynamic Light Scattering
I_{sc}	Short circuit current
CGS	Co-generation system
J_{sc}	Short circuit density
MCS	Mono-crystalline silicon
PCS	Poly-crystalline silicon

Abbreviations

ITO	Indium Tin Oxide
LSPR	Local surface plasmon resonance
SEM	Scanning electron microscopy

silicon solar cells. In another study, Sreeja and Pesala (2020) studied the effect of the distribution of silver nanoparticles on photovoltaic characteristics of betanin-lawsone co-sensitized solar cells and Jbira et al. (2020) used silver nanoparticles to optimize the photovoltaic properties of silicon nanowires. Bhattacharjee and Dasgupta (2020) have also studied the application of silver nanoparticles for thin-film solar cell applications. Perovskite solar cells are another type of solar cells which Eli et al. (2020) have worked on optimizing by adding silver nanoparticles. Moreover, Rehman (2020) have used silver nanoparticles in dye-sensitized solar cells to increase the absorption efficiency of these solar cells.

Another parameter which may affect the characteristics of solar cells, including nanoparticles, is the shape, structure, size, place and distribution of the nanoparticles. Rehman (2020) studied a different location for adding silver nanoparticles and designed a silicon solar cell with a silver nanoparticle-coated back reflector. In another similar study, Moulin et al. (2008) used two different sizes of silver nanoparticles in the back contact of thin-film silicon solar cells.

Starowicz (2017) applied silver nanoparticles with a size range of 100 to 140 nm to a silicon solar cell and reported a 12 % increase in short circuit density. Birant et al. (2020) applied silver nanocubes on monocrystalline silicon solar cells using the spraycoating method to enhance the properties of silicon solar cells. In another study, Piralaee and Asgari (2020) modeled the effect of silver nanoparticles on InGaN/GaN solar cells. Mohsin et al. (2020) have simulated the effect of adding silver nanoparticles on the light-trapping properties of thin film solar cells. A group of studies have focused on the modelling and simulation of the application of silver nanoparticles in solar cells. In this regard, Pylypova et al. (2020) used a combination of silicon nanowires and silver nanoparticles to enhance the light-trapping properties of solar cells. Further Pylypova (2021), studied the effect of the geometry of the silicon nanowires on the properties of these solar cells.

In another study, Temple et al. (2009)) have studied the effect of adding silver nanoparticles to common silicon solar cells. The silver nanoparticles in this method have been added using electron beam evaporation which is a complicated and expensive method. Finally, the study has reported an approximately 1 % increase in the efficiency of the solar cells after the deposition of the silver nanoparticles.

A variety of studies have already been conducted regarding the application of nanoparticles for the optimization of solar cells and specific applications of silver nanoparticles for these purposes. But the previous studies have added the nanoparticles to ordinary silicon solar cells. In this study, silver nanoparticles are added to a specific type of silicon solar cells named as hybrid silicon solar cells. Hybrid silicon solar cells are a group of silicon solar cells which have a very simple and cost-effective production process compared to the methods used in the literature, but also have a better performance compared to typical silicon solar cells (Shiraz et al., 2016). Therefore, silver nanoparticles may be added to hybrid silicon solar cells, to add the local surface plasmon resonance to this type of solar cells. Although the method used for the addition of silver nanoparticles may vary as well. Common methods used in the literature for the addition of silver nanoparticles to solar cells include high-tech and costly methods and equipment. The method used in the present research for the production of silver nanoparticles is a simple and cost-effective method. Furthermore, drop casting method has been proposed for the deposition of the silver nanoparticles on the surface which is a very simple and cost-effective method.

2. Materials and methods

In this section, the materials used in the research have been introduced in the first section, and then the methodology has been explained in detail in the second section. Hybrid silicon solar cells are a group of solar cells based on crystalline silicon. Fig. 1 shows a schematic of the structure of a hybrid silicon solar cell, which was fabricated by Shiraz et al. (2016). According to Fig. 1, hybrid silicon solar cells are made of four layers including, an aluminum layer acting as the backside contact metal, a crystalline silicon layer acting as the P-type semiconductor, a titanium dioxide layer acting as the N-type semiconductor, and an Indium Tin Oxide (ITO) layer which is a transparent meanwhile conductive layer acting as the charge transfer layer.

Hybrid silicon solar cells are an implementation of silicon solar cells with a simple method to provide a p-n junction for silicon solar cells. The hybrid silicon solar cell may be easily fabricated without the need for complicated devices and methods. However, the performance of these silicon solar cells were lower compared to conventional samples. This study has evaluated the addition of silver nanoparticles to the cells in a simple and easy way to enhance cell performance of hybrid silicon solar cells without affecting the fabrication method simplicity. In this study, silver nanoparticles with different properties have been added in between the different layers of the hybrid silicon solar cells and studied separately to find the optimum situation and optimum properties of the added silver nanoparticles. The method of fabricating hybrid silicon solar cells and the method of fabricating silver nanoparticles are described in detail. Further the silver nanoparticles are deposited in different situations between the different layers of the hybrid silicon solar cells and the performance of the cell is studied to observe the optimum location for the addition of the silver nanoparticles. Afterward, the silver nanoparticles' properties are manipulated to obtain optimum results.

2.1. Materials

Titanium Dioxide (P-25) was obtained from Degussa AG, Germany; Ammonia, Silver Nitrate, Monocrystalline silicon wafers (1 0 0) orientation, Glucose, Ethanol, and Acetone were obtained from Merck Company and were used as received without further purification. All solutions were prepared using deionized water as solvent.

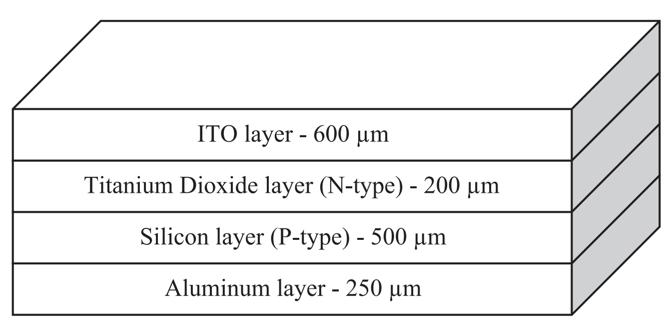

Fig. 1. A schematic of the structure of a hybrid silicon solar cell (Shiraz et al., 2016).

2.2. Preparation of the crystalline silicon sample

The base part of the hybrid crystalline silicon solar cells is a silicon wafer. In this study, P-type monocrystalline silicon wafers with a (1 0 0) crystal orientation and specific resistance of 0.1 O per square centimeter were used as the silicon wafer. The silicon wafers used in this research have a thickness of 800 μm, with a back layer of aluminum. The P-type monocrystalline silicon wafers are cut into smaller samples with a dimension of 1 cm x 1 cm. The samples are first washed with water and soap to remove dust and contaminations from their surface. Further, to remove any remaining contaminations, the samples are placed in an acetone solution in an ultrasonic bath for 6 min, then placed in an ethanol solution in the ultrasonic bath for another 6 min to ensure that the surface of the samples is free from any contaminations. Finally, the samples are rinsed using deionized water and dried. In this step, the electrical resistance of the silicon wafer samples is measured and if the resistance has decreased, the samples are ready for the deposition of the new layers.

2.3. Fabrication of titanium dioxide nanoparticles layer

Another layer of the hybrid crystalline silicon solar cell is the titanium dioxide nanoparticle layer. In this study, the titanium dioxide layer has been deposited on the surface using electrophoresis method. The electrophoresis method is one of the colloidal methods with advantages such as short timing, simple equipment, and the small number of limitations regarding the substrate. Moreover, as this method is a wet method, the thickness and morphology of the deposition layer may be manipulated easily, by changing the process time and voltage.

A solution including titanium dioxide nanoparticles is required for the electrophoresis of the titanium dioxide layer. This solution is prepared by mixing 0.05 g of titanium dioxide, 2 ml of Acetone and 60 ml of Isopropyl Alcohol and stirring the mixture to obtain a homogenous solution of titanium dioxide nanoparticles. Then the crystalline silicon samples are placed in an electrophoresis circuit, which is shown in Fig. 2. By applying an electric current with a voltage of 200 V for five minutes, a layer of titanium dioxide nanoparticles is deposited on the surface.

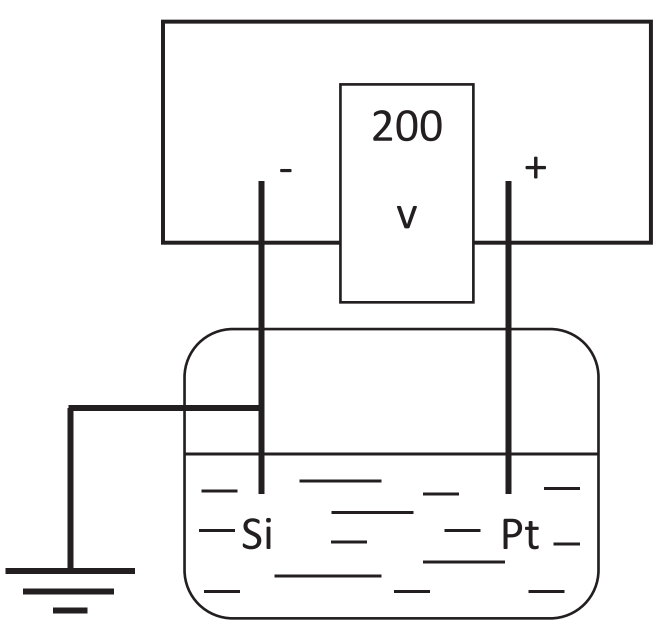

Fig. 2. The schematic diagram of an electrophoresis circuit.

2.4. Fabrication of the silver nanoparticles layer

The silver nanoparticles are fabricated through Tollens method (Jiang, et al., 2013). According to Tollens method, first, silver nitrate is added to deionized water and stirred to produce a silver nitrate solution. Then ammonia is added in a dropwise manner to obtain a brown solution, according to chemical reaction (1):

$$2Ag^{+}_{(aq)} + 2OH^{-}_{(aq)} \rightarrow Ag_2O_{(s)} + H_2O_{(l)} \tag{1}$$

Ammonia is added again in a dropwise manner to obtain a transparent solution according to chemical reaction (2):

$$Ag_2O_{(s)} + 4NH_{3(aq)} + H_2O_{(l)} \rightarrow 2\left[Ag(NH_3)_2\right]^{+}_{(aq)} + 2OH^{-}_{(aq)} \tag{2}$$

At this stage, a KOH solution is produced separately, by adding KOH to deionized water. The KOH solution is added to the solution in a dropwise manner, according to chemical reaction (3):

$$2\left[Ag(NH_3)_2\right]^{+}_{(aq)} + 2OH^{-}_{(aq)} \rightarrow Ag_2O_{(s)} + 4NH_{3(aq)} + H_2O_{(l)} \tag{3}$$

Ammonia solution is added again in a dropwise manner, according to chemical reaction (4):

$$Ag_2O_{(s)} + 4NH_{3(aq)} + H_2O_{(l)} \rightarrow 2\left[Ag(NH_3)_2\right]^{+}_{(aq)} + 2OH^{-}_{(aq)} \tag{4}$$

A glucose solution is produced separately, by adding glucose to deionized water. The glucose solution is added to the solution of the previous step and stirred, to obtain a solution of silver nanoparticles according to chemical reaction (5).

$$(C_5H_{11}O_5) - CHO_{(aq)} + 2\left[Ag(NH_3)_2\right]^{+}_{(aq)} + 2OH^{-}_{(aq)} \leftrightarrow (C_5H_{11}O_5) - CHO_{(aq)} + 2Ag_{(s)} + 4NH_{3(aq)} + H_2O_{(l)} \tag{5}$$

Then a specific amount of the silver nanoparticle solution is applied on the sample surface using drop-cast method.

2.5. Fabrication of Indium Tin Oxide layer

In this study, a layer of Indium Tin Oxide (ITO) is used as the top surface, acting as a transparent, conductive layer that protects the cell. The ITO layer helps with charge transfer and lets light pass through. Accordingly, an ITO layer with a thickness of 500 to 700 nm is deposited on the substrate using the sputtering method. The methods described in this chapter are applied to construct hybrid crystalline silicon solar cells incorporating different layer combinations or different properties of silver nanoparticles to find the optimum properties and combinations. These methods will be discussed in detail in the subsequent section.

2.6. Various combination of the layers

An important factor affecting the performance of the hybrid silicon solar cell is the combination of the layers. Following the description of the overall process used to fabricate the hybrid crystalline silicon solar cells and silver nanoparticles, in this section, we have studied the best way to combine the layers to achieve the maximum performance of the solar cell. Fig. 4 shows a schematic of the layers included in a hybrid silicon solar cell. As shown in Fig. 3 the layers from the bottom to the top include the aluminum layer which is referred to as Al, the p-type crystalline silicon layer which is referred to as Si, the TiO_2 layer which is referred to as TiO_2 and the ITO layer which is referred to as ITO. In order to study the best combination whereas to introduce the silver nanoparticles, different samples with different combinations of layers from the bottom to the top have been fabricated which are listed below:

a) Al- Si- TiO_2- ITO (the ordinary hybrid silicon solar cell)

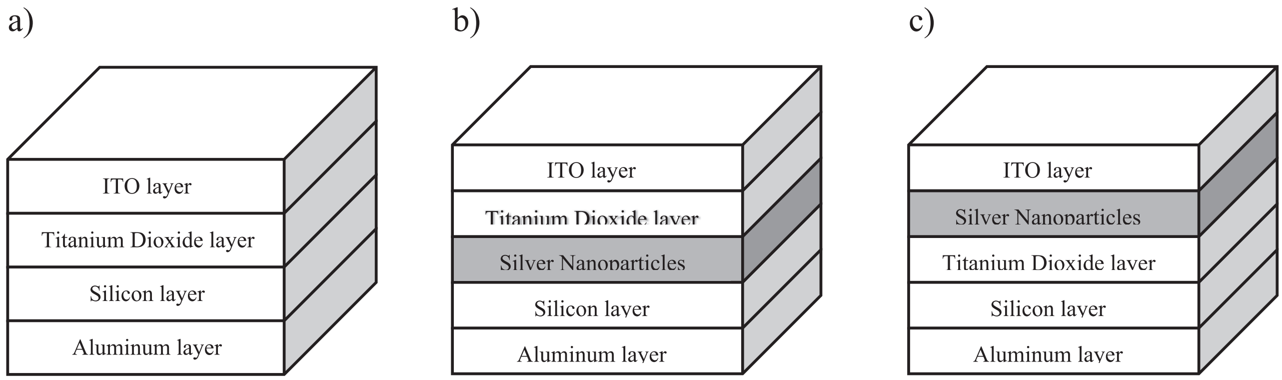

Fig. 3. A) a schematic of an ordinary hybrid silicon solar cell; a schematic of a hybrid silicon solar cell including silver nanoparticles b) between the silicon and titanium dioxide layer; and c) between the ito and titanium dioxide layer.

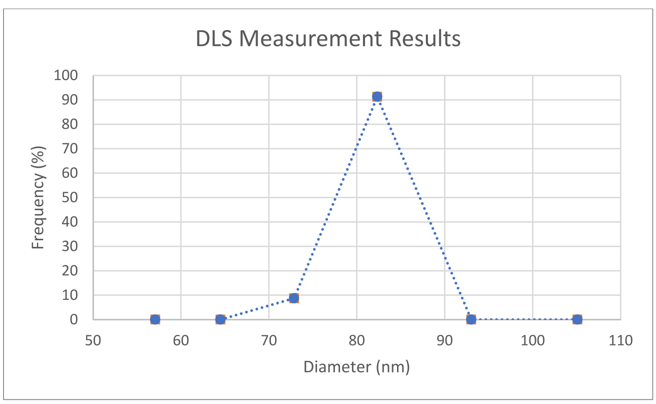

Fig. 4. The DLS test results of the synthesized silver nanoparticles.

b) Al- Si- Ag- TiO_2- ITO
c) Al- Si- TiO_2- Ag- ITO

2.7. Characterization tests

One of the properties of the silver nanoparticles which affect the performance of the hybrid silicon solar cells is the size of the synthesized silver nanoparticles. In this research, the size distribution of the silver nanoparticles was studied using the dynamic light scattering (DLS) method. DLS is a method used to study the size distribution profile of small particles in solutions or suspensions. Therefore, in order to study the size distribution profile of silver nanoparticles, the solution containing the silver nanoparticles was used as the DLS sample. The DLS test was performed using a Horiba scientific SZ-100 device at room temperature.

Another factor which may affect the performance of the hybrid silicon solar cell is the distribution of the silver nanoparticles on the surface of the cell and also the surface morphology of the silver nanoparticles. In this regard scanning electron microscopy (SEM) method was used to take pictures of the surface containing the silver nanoparticles in order to find out the distribution and the shape of the silver nanoparticles on the surface. The surface morphology and distribution of silver nanoparticles on the layers were examined using a Zeiss DSM-960A scanning electron microscope.

One of the parameters which are important in evaluating the performance of solar cells is their Current-Voltage (I-V) graph. An I-V graph is used to determine parameters like the short circuit current and open circuit voltage. After fabricating the hybrid silicon solar cells containing silver nanoparticles, the samples are placed in a sun simulator to obtain the I-V graph of the samples in dark mode and light mode by a Sama500 potentiostat device. Further the data provided from the I-V graph were used to calculate the Fill Factor and the energy conversion efficiency of the solar cells. The short circuit current and open circuit voltage represent the maximum current and voltage which may be produced by the solar cell, although the energy produced at these two points is zero. Therefore, another factor which is known as the fill factor (FF) is introduced. Fill factor is defined using the equation below:

$$FF = \frac{V_{MP} I_{MP}}{V_{OC} I_{SC}}$$

Wherein V_{MP} refers to the voltage at the maximum power point, I_{MP} is the current at the maximum power point, V_{OC} is the open circuit voltage, and I_{SC} is the short circuit current of the cell. FF is also defined as the squareness factor of the I-V graph.

Another crucial parameter in solar cells is the energy conversion efficiency. The energy conversion efficiency may be calculated using the equation below:

$$\eta = \frac{P_{max}}{P_{in}} = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

Wherein P_{in} is the input power of the solar cell and P_{max} is he maximum power of the solar cell. The energy conversion efficiency and fill factor of the solar cells fabricated in this research are further calculated and used as parameters to compare different implementations and find optimum properties for enhanced performance in the produced solar cells.

3. Results and discussion

Various tests have been conducted to determine the properties of the fabricated solar cells as well as those of the silver nanoparticles after fabrication. In order to study the properties of the silver nanoparticles regarding the size distribution of the particles, a dynamic light scattering (DLS) test has been used which the results are further described in detail. Further scanning electron microscopy (SEM) has been used to study the surface morphology of the samples and the alignment of the silver nanoparticles on the surface. Finally, I-V characterization tests were used to evaluate the performance of the implementations of the hybrid silicon solar cells with silver nanoparticles.

3.1. Dynamic light scattering (DLS) test

The size distribution of the silver nanoparticles produced according to the method of the previous section have been studied using Dynamic Light Scattering (DLS) method. DLS uses the concept of Brownian motion of dispersed particles, referring to the collision of the dispersed particles with solvent molecules in a solution. The particle size is measured in DLS method according to the changes in the intensity of light scattered from the solution. The DLS test was performed using a HORIBA SZ-100 V2 device to measure the particle size, which can measure particle sizes from 0.3 nm to 10 μm. The scattering angle in the measurement was 90°, the holder temperature was 25.1C, and the dispersion medium viscosity was 0.893 mPa.s. In count rate of the measurement was 349 kCPS.

The results of the DLS test are shown in Fig. 4. According to Fig. 4, ensemble collection of particles was found 61.1 nm and the poly-dispersity index was 2.431. The silver nanoparticles in the solution, have diameters ranging from approximately 60 to 100 nm, which confirm the nanoscale dimension of the synthesized silver particles. According to Santbergen et al. (Santbergen et al., 2012), the preferred size of the silver nanoparticles for use in solar cells has been reported to be in the range of 50 to 100 nm. Therefore, the size of the synthesized nano-particles is in the preferred range.

3.2. I-V characterization

As mentioned above the I-V graph is one of the methods of evaluating important parameters of silicon solar cells, such as the short-circuit current and the open-circuit voltage of these cells. In this regard, first, an ordinary hybrid silicon solar cell with the layer combination of (Al - Si - TiO_2 - ITO) was synthesized. A sun simulator was utilized to evaluate the performance of the sample. This enabled further comparisons between hybrid silicon solar cells including silver nanoparticles and ordinary hybrid silicon solar cells. Fig. 5 shows the I-V graph of the hybrid silicon solar cell before the addition of silver nanoparticles.

According to Fig. 5, the hybrid silicon solar cell without silver nanoparticles has an open-circuit voltage of about 6 mV and a short-circuit current of about $1.7\mu A$, which are both very small and have a low performance as a solar cell. In an implement, silver nanoparticles were drop casted on to the silicon wafer after preparing the silicon wafer, and then the titanium dioxide layer was deposited on top of the silver nanoparticle layer and finally the ITO layer was applied, producing a sample named b, with the layer combination of (Al- Si- Ag- TiO_2- ITO). The I-V graph of sample b is shown in Fig. 6 below.

According to Fig. 6, comparing the sample performance in light and dark conditions reveals that the sample exhibits photodetector behavior, whereas the current changes in response to light, however, as the short circuit current of this sample is positive and nearly zero, the sample does not have photovoltaic characteristics. This is attributed to the addition of conductive silver nanoparticles within the depletion region, positioned between the silicon layer (p-region) and the TiO_2 layer (n-region), establishing a direct electrical pathway that effectively short-circuits the current across the p-n junction. As a consequence, electric charges can freely traverse between the p and n regions, resulting in the loss of photovoltaic properties.

In another combination, the silver nanoparticles have been deposited between the titanium dioxide layer and the ITO layer producing a

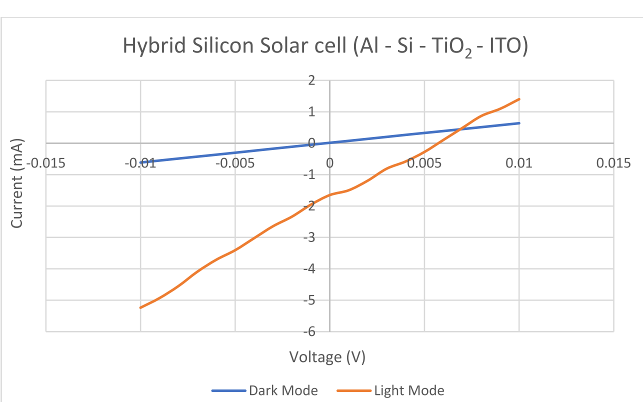

Fig. 5. The current – voltage graph of an ordinary hybrid silicon solar cell (Al - Si - TiO_2 - ITO) in dark and light mode.

sample named c, with a layer combination of (Al- Si- TiO_2- Ag- ITO). In sample c, first the Titanium dioxide layer is applied on the silicon samples, then the silver nanoparticles are drop-casted, and finally the ITO layer is applied. Further the characteristics of sample c, as a photovoltaic cell have been studied. Fig. 8 shows the I –V graph of sample c.

As can be seen in Fig. 7, sample c has a negative short circuit current; therefore, sample c has photovoltaic properties. Moreover, the short circuit current and the open-circuit voltage of sample c were −6.188 μA and 2.5 mV, respectively; which show the enhancement in photovoltaic properties of the hybrid silicon solar cells containing silver nanoparticles with a combination of (Al- Si- TiO_2- Ag- ITO) compared to the ordinary one.

As a conclusion to this section, it can be mentioned that the deposition of silver nanoparticles on top of the titanium dioxide layer resulting in a sample with a combination (Al- Si- TiO_2- Ag- ITO), enhances the properties of the hybrid silicon solar cell compared to the ordinary hybrid silicon solar cell. But the deposition of silver nanoparticles on the silicon wafer and then fabricating the other layers which result in the formation of a layer with a combination of (Al- Si- Ag- TiO_2- ITO), results in a short circuit, between the p-n junction in the two parts of the solar cell due to electrical conductivity of the silver nanoparticles, and the samples with the latter combination (Al- Si- Ag- TiO_2- ITO) only have photodetector properties. Accordingly, Kalfagiannis et al. (Kalfagiannis, 2012) have also confirmed that the place of the silver nanoparticles can affect the performance of the solar cell.

3.3. SEM characterization

In order to confirm the existence of silver nanoparticles and to study the surface morphology of the silver nanoparticle islands deposited on the titanium dioxide layer, the scanning electron microscopy (SEM) method has been used. Fig. 8 shows an SEM image of silver nanoparticles drop casted from a solution of silver nanoparticles with a concentration of 100 %vl. on the surface of the silicon wafer.

As can be seen in Fig. 8, the conductive silver nanoparticles applied on the surface of the silicon, have produced islands. These islands have formed a pathway which have resulted in a short circuit between the p layer which is the silicon layer and the n layer which is the titanium dioxide layer of the cell, causing sample b to lose its solar cell properties due to the short circuit between the p and n layers of the cell. Fig. 9 shows an SEM image of silver nanoparticles drop casted on the titanium dioxide layer resulting in a combination of (Al- Si- TiO_2- Ag).

Fig. 9 A top-view SEM showing the islands formed by silver nanoparticles on the surface of the Titanium dioxide layer.

According to Fig. 9, silver nanoparticles have been deposited on the surface of the titanium dioxide layer. The silver nanoparticles have produced islands with a size range of micrometers. Even though silver nanoparticles are electrically conductive because they are deposited on top of the p-n junction and not between the p and n layers, they have not destroyed the photovoltaic properties of the hybrid silicon solar cell. But on the other hand, the deposited silver nano particles act as a barrier in front of the radiated light and thereby decrease the active surface of the cell.

3.4. Concentration of silver nanoparticles

The previous section found the optimum location for adding the silver nanoparticles to hybrid silicon solar cells, which resulted in the (Al- Si- TiO2- Ag- ITO) combination. It should be noted that although adding silver nanoparticles may enhance the performance of the solar cell due to local surface plasmon resonance, but silver nanoparticles are opaque and meanwhile decrease the active surface of the photovoltaic cell, by acting as a barrier for the light radiating on the cell which is also discussed by Akimov et al. (Akimov et al., 2009). Therefore, there is an optimum for the amount of silver nanoparticles deposited on the surface

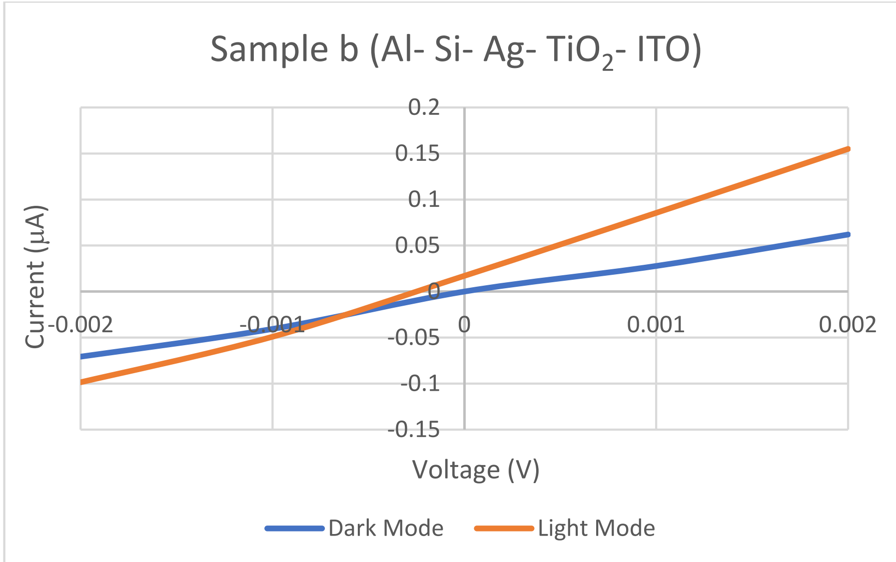

Fig. 6. The current – voltage graph of sample b with a layer combination (Al- Si- Ag- TiO_2- ITO) in dark and light mode.

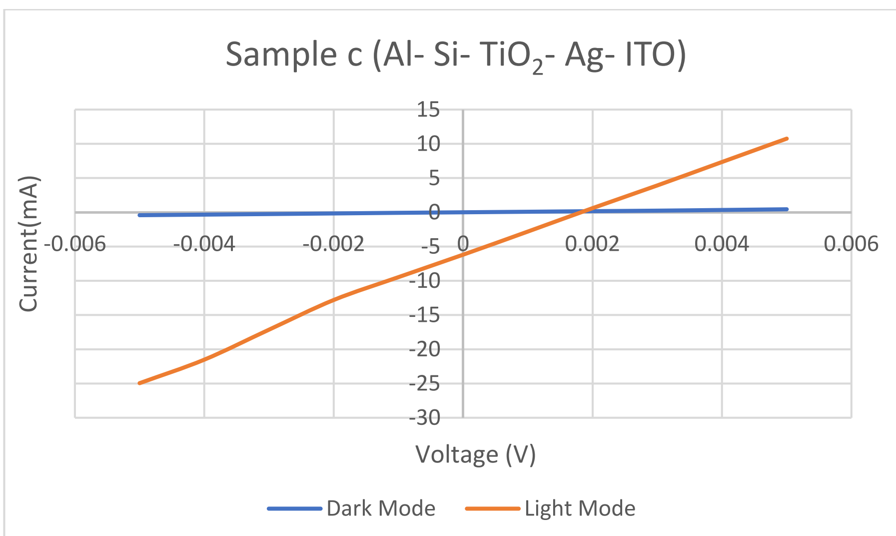

Fig. 7. The current – voltage graph of sample c with a layer combination (Al- Si- TiO_2- Ag- ITO) in dark and light mode.

of the hybrid silicon solar cell. In this section different concentrations of silver nanoparticles have been deposited on the titanium dioxide layer, to find the optimum surface distribution. The method used for manipulating the silver nanoparticles' surface distribution is by adjusting the concentration of the silver nanoparticles solution by adding deionized water. For this reason, different solutions of silver nanoparticles with concentrations of 100 vl%, 75 vl%, 50 vl%, 40 vl%, 25 vl% and 10 vl% compared to the original silver nanoparticle have been produced. Further each of the solutions have been deposited on separate samples to produce samples named as below:

1) Al- Si- TiO_2- Ag 100 %- ITO
2) Al- Si- TiO_2- Ag 75 %- ITO
3) Al- Si- TiO_2- Ag 50 %- ITO
4) Al- Si- TiO_2- Ag 40 %- ITO
5) Al- Si- TiO_2- Ag 25 %- ITO
6) Al- Si- TiO_2- Ag 10 %- ITO

SEM images of samples 1 (Al- Si- TiO_2- Ag 100 %- ITO) and 2 (Al- Si- TiO_2- Ag 75 %- ITO) are shown in Fig. 10, in order to visualize the effect of the concentration of silver nanoparticles solution on the surface distribution of the silver nanoparticles.

According to Fig. 10, sample 3 (Al- Si- TiO_2- Ag 50 %- ITO) is produced using a 50 vl% concentration of silver nanoparticles which is shown in Fig. 10a. Sample 1 (Al- Si- TiO_2- Ag 100 %- ITO) which is produced using a 100 vl% concentration of silver nanoparticles is shown in Fig. 10b. As can be seen in Fig. 10, sample 3 has a lower surface distribution, compared to sample 1. Moreover, the silver nanoparticle islands of sample 3 (Al- Si- TiO_2- Ag 50 %- ITO) are smaller compared to the silver nanoparticle islands of sample 1 (Al- Si- TiO_2- Ag 100 %- ITO). The smaller silver nanoparticle islands in sample 3 cause less shading and do not reduce the active surface of the solar cell as much as sample 1. All samples have photovoltaic properties. Moreover, by decreasing the concentration of the silver nanoparticles, the short-circuit current and the open-circuit voltage start to increase and by reaching a concentration of 50 %vl, the short-circuit current and the open-circuit voltage both reach their maximum amounts. By further decreasing the concentration of the silver nanoparticles to less than 50 %vl, the short-

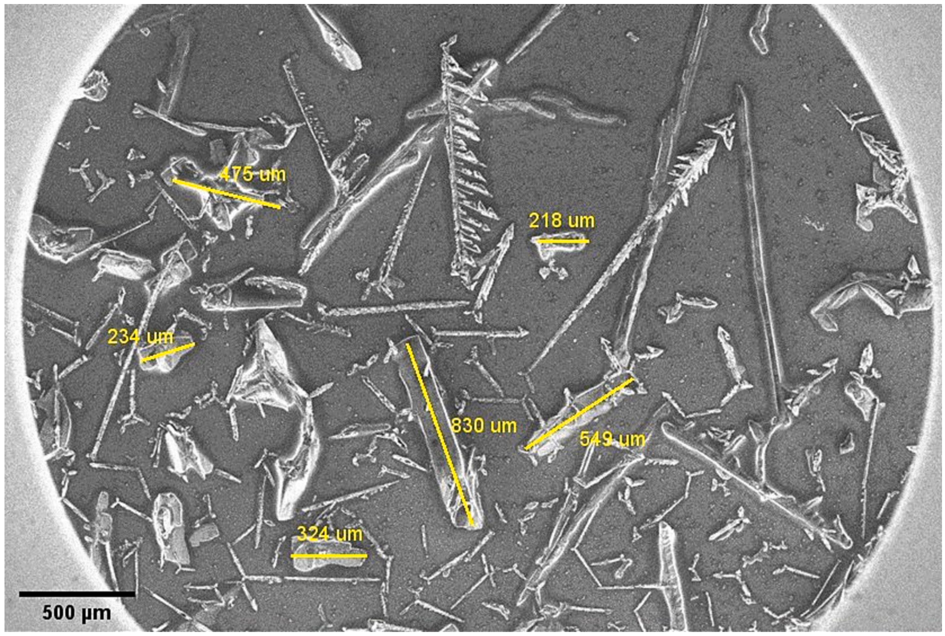

Fig. 8. SEM image showing the distribution of the silver nanoparticle islannds dropcasted from a solution of silver nanoparticles with a concentration of 100 %vl. on the surface of silicon wafer.

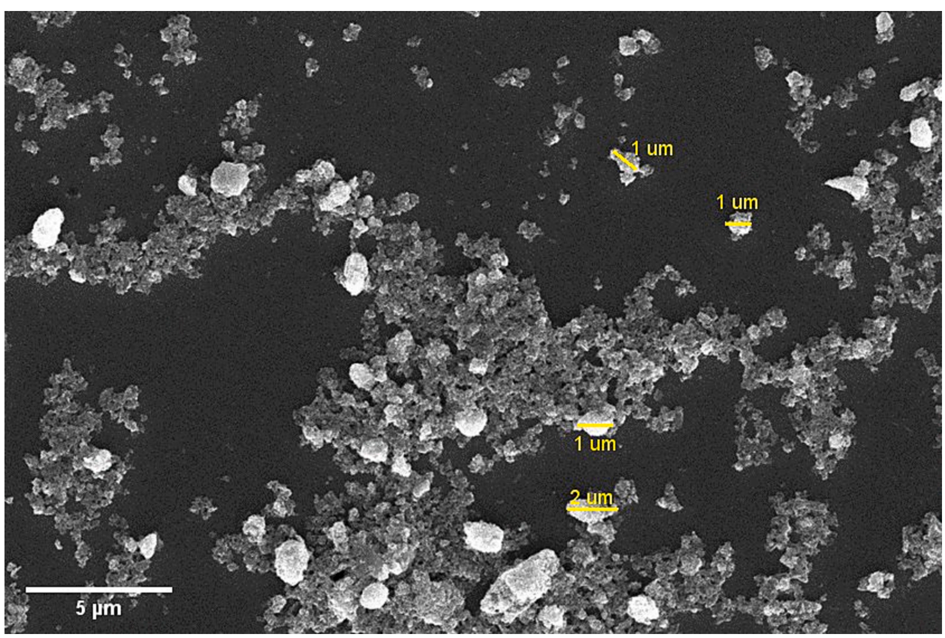

Fig. 9. A top-view SEM showing the islands formed by silver nanoparticles on the surface of the Titanium dioxide layer.

circuit current and the open-circuit voltage again begin to decrease.

Fig. 11 shows the short circuit current of samples with different concentrations of silver nanoparticles and Fig. 12, shows the open- circuit voltage of the samples, for better comparison. According to the diagrams, by decreasing the concentration of silver nanoparticles, both the short-circuit current and open-circuit voltage begin to increase, which generally means that the solar cell's overall performance enhances. By reaching a 50vl% concentration of silver nanoparticles compared to the primary solution both the short-circuit current, and open- circuit voltage increase compared to the previous samples, but by decreasing the concentration to less than 50vl% concentration, the short-circuit current and open- circuit voltage start to decrease.

Fill factor and energy conversion efficiency are two known parameters which may be used to evaluate the performance of solar cells. Therefore, to better compare the characteristics of the produced hybrid silicon solar cells according to the different concentration of silver nanoparticles, the fill factor and power conversion efficiency of the produced samples have been calculated which have been shown in the graphs below.

As can be seen in Fig. 13 and Fig. 14, the hybrid silicon solar cell with a 50vl% had a significantly higher fill factor and power conversion efficiency compared to the samples with lower and higher concentrations of silver nanoparticles. From one point of view, the incorporation of silver nanoparticles may offer advantages such as improving the optical behavior and triggering the local surface plasmon resonance (LSPR) phenomenon, thereby enhancing the performance of the solar cell.

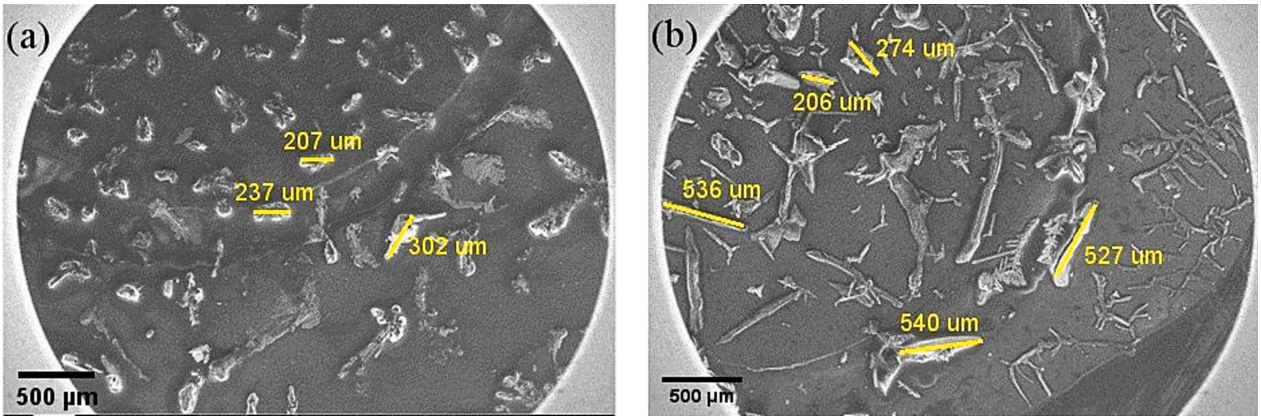

Fig. 10. SEM images of (a) sample 3 (Al- Si- TiO_2- Ag 50%- ITO) and (b) sample 1 (Al- Si- TiO_2- Ag 100%- ITO).

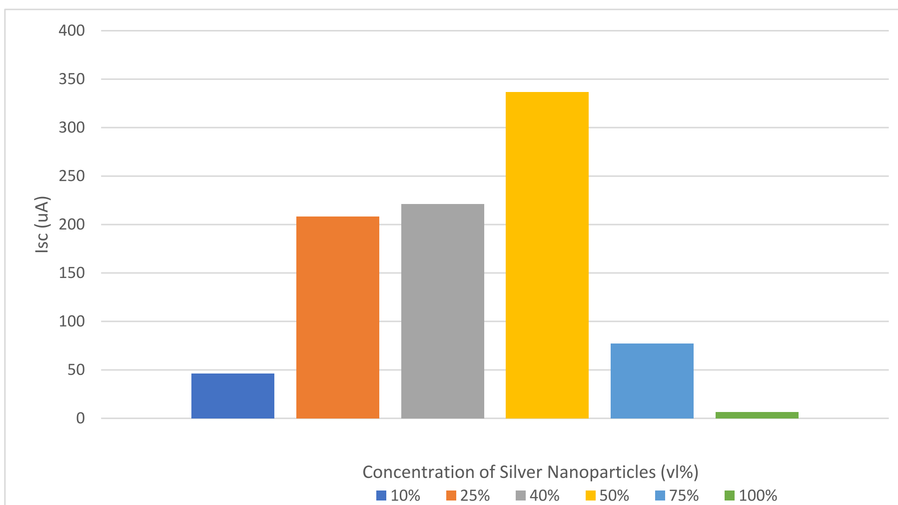

Fig. 11. A diagram comparing the short circuit currents of hybrid silicon solar cells including different concentration of silver nanoparticles.

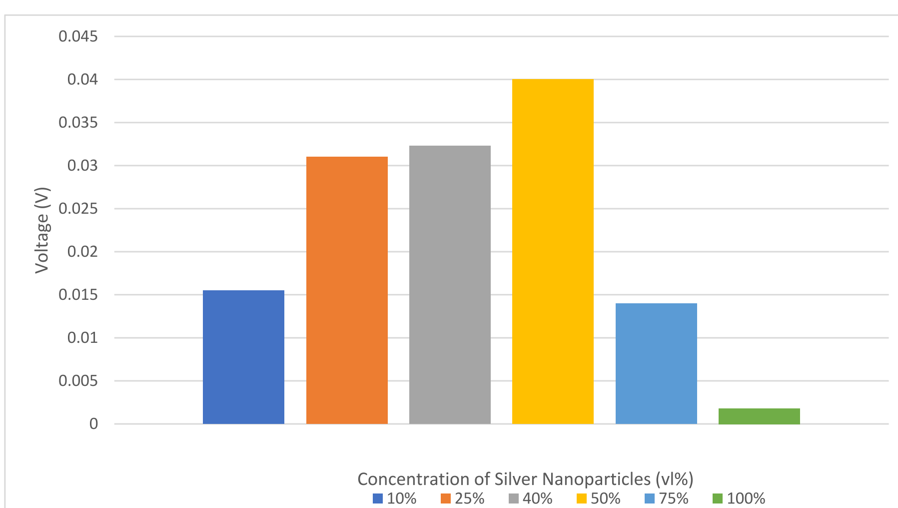

Fig. 12. A diagram comparing the open circuit voltage of hybrid silicon solar cells including different concentration of silver nanoparticles.

Moreover, the silver nanoparticles possess notable electrical conductivity which may facilitate charge transfer in the solar cell. However, from another perspective, silver nanoparticles are not transparent and cast shadows on the surface of the silicon solar cell thereby diminishing the area of the cell exposed to solar radiation which may have a negative impact on the performance of the cell. Consequently, it can be concluded that there exists an optimal concentration for the deposition of silver nanoparticles onto the surface of the hybrid silicon solar cell, which, in

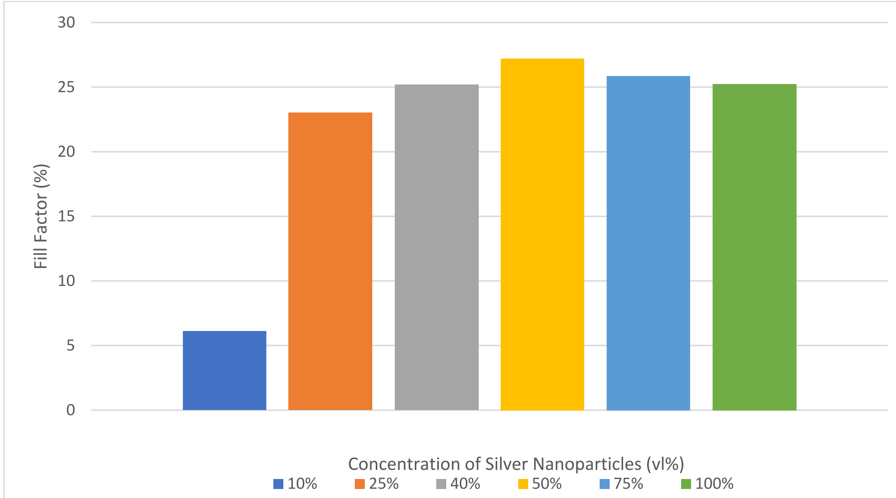

Fig. 13. A diagram comparing the fill factor of hybrid silicon solar cells including different concentration of silver nanoparticles.

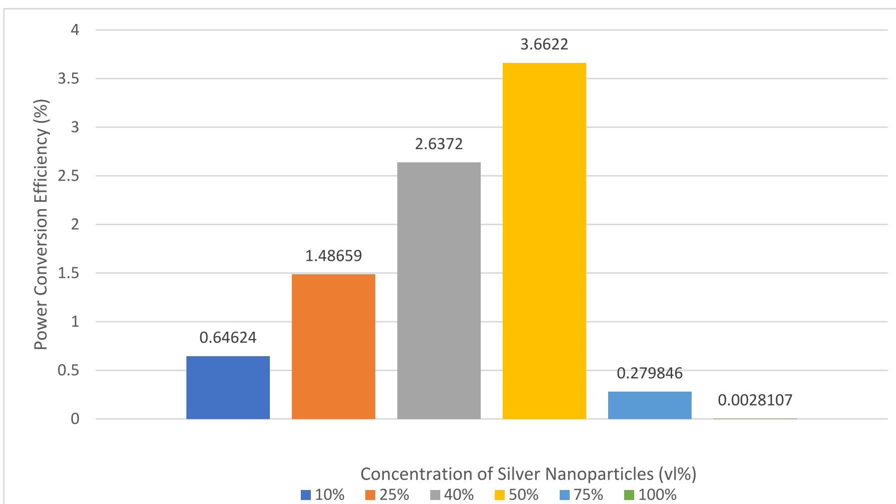

Fig. 14. A diagram comparing the power conversion efficiency of hybrid silicon solar cells including different concentrations of silver nanoparticles.

this study, is determined to be 50 vol%. At this concentration, the combined influence of positive and negative effects culminates in the optimal performance of the solar cell.

It is worth to mention that the aim of the present study is to evaluate the effect of the silver nanoparticles on hybrid silicon solar cells and the optimum concentration to obtain best performance. The method used in the present study are very simple and very cost-effective, which may be easily carried out in a common lab. It may be noticed that the performance of the produced solar cells is not comparable with common crystallin silicon solar cells. It should be noted that the aim and scope of the present study is focused on the application of silver nanoparticles and their effect and the optimization of the hybrid silicon solar cells may be further investigated in future research.

4. Conclusion

Silicon solar cells have been known and used for a long, but one of the deficiencies of these cells is their low efficiency, costly and difficult production process. As an implementation hybrid silicon solar cell have been introduced which have an easier and cost-effective production process. Moreover, metal nanoparticles have been known to enhance the performance of silicon solar cells due to their local surface plasmon resonance effect. Therefore, this study has added silver nanoparticles to hybrid silicon solar cells to simultaneously derive both the advantages of hybrid silicon solar cells and the local surface plasmon resonance of silver nanoparticles. Two different combinations were considered for the deposition of silver nanoparticles on the hybrid silicon solar cell which were (Al- Si- TiO_2- Ag- ITO) and (Al- Si- Ag- TiO_2- ITO). It was found that the addition of silver nanoparticles to the hybrid silicon solar cell with a combination of (Al- Si- TiO_2- Ag- ITO) enhances the properties of the cell including the short circuit current and open circuit voltage due to the plasmonic effect of silver nanoparticles. Although, silver nanoparticles enhance the performance of silicon solar cells but they also cause shading on the surface of cells, which reduces their efficiency. As a result, there is an optimum distribution for silver nanoparticles on the surface of the solar cell to both benefit from the localized surface plasmon resonance and not to cover a vast amount of the surface and reduce its active surface area. Accordingly, different concentrations of silver nanoparticle solutions were prepared and deposited on the solar cell to find the optimum surface distribution of silver nanoparticles. According to the results, the optimum concentration of silver nanoparticles solution was 50 %vl, which resulted in maximum photovoltaic performance in hybrid silicon solar cells. The solar cell including a 50 %vl silver nanoparticles concentration, had an energy conversion efficiency of

3.66 %, however the energy conversion efficiency of the 100 %vl was 0.03 % and the energy conversion efficiency of the 10 %vl was 0.65 %, which approves the optimum results achieved by the 50 %vl concentration. Finally, it should be noted that the present study has approved the positive impact of the addition of silver nanoparticles on the performance of hybrid silicon solar cells. Moreover, the optimum concentration of silver nanoparticles for optimum performance where found. However, the prepared hybrid silicon solar cells may be further improved in future studies. Another group of future studies may include the study of different methods of adding the 50 %vl silver nanoparticles, to increase accuracy.

CRediT authorship contribution statement

Armin Shamaeizadeh: Data curation, Investigation, Visualization, Writing – original draft. **Fatemeh Razi Astaraei:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **Alibakhsh Kasaeian:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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